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Textile Transmission Lines in the Modern Textronic Clothes

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Abstract

This article describes textile transmission lines, one of the important elements of modern textronic clothing. The paper describes the classification of these lines with regard to the application area and discusses the basic electrical parameters which determine their suitability for the transmission of signals of a wide frequency spectrum. The paper also discusses the main difficulties related to the design and implementation of transmission lines, such as resistance to mechanical stress and washing, and the change in environmental conditions. The paper also presents examples of measurements of wave propagation in textile transmission lines for different degrees of moisture of the textile substrate of the line. These measurements showed that the substrate humidity has a significant effect on the electrical parameters of the line.

Key words: *textronics, smart textiles, textile transmission line, textile signal line.*

Introduction

In recent years we have seen a rapid development of intelligent materials applicable in the construction of smart garments. The new field of science dealing with the implementation of electroconductive materials, various types of modern sensors as well as electronic and computer systems in textiles is called textronics [1, 2]. In short, this area is a combination of textiles, electronics and informatics. Possible applications of textronic systems are enormous, ranging from traditional entertainment such as music players and the implementation of GSM systems in clothes, up to physiological parameter monitoring systems applicable for personal protection systems against various types of threats used by firefighters, soldiers, policeman etc. Examples of such systems are presented in [3], [4]. Textiles equipped with multiple sensors of physiological parameters and a radio system for the transmission of measurement data can also be used in the continuous monitoring of the health status of patients, enabling continuous medical supervision also when they are outside of the hospital. Numerous institutions around the world are active in designing the systems described above. The current state of technological advancement in textronics causes that smart clothing prototypes mostly comprise conventional electronic components connected by transmission lines in the form of conventional wires. However, great effort is being made to replace conventional transmission lines by ones containing a conductive path often made of textile structures placed directly on a flat textile product at the production stage. In the case of production of longer series this should reduce significantly the cost of manufacturing intelligent clothing and increase its reliability. Such lines may have a path in the form of conductive fibers or yarns supplying power to electronic components, or transmit digital or analog signals. Therefore they are an important part of any textronic system.

The aim of the article is to present a classification of textile transmission lines according to their structure, destination, basic transmission parameters and problems involved with their application. An example of the humidity influence of the embedding medium, according to measurements carried out by the author, is also given.

Methods of the implementation of textile transmission lines

Currently, there are many possibilities of implementing a transmission line into a textile substrate:

- direct implementation of conductive transmission lines in the form of conductive wires (also insulated) or electroconductive yarns at the production stage and manufactured in flat textile products such as woven fabrics, knittings and nonwovens
- overprinting an electroconductive medium on a flat textile
- spraying or other deposition of an electroconductive medium on a flat textile
- incorporating electroconductive paths using sewing or embroidery methods.

In the first method, already at the production stage, e.g. during the process of weaving, electroconductive elements in the form of copper wires or yarns are placed in the flat textile as an integral part of the structure. An example of such a fabric is shown in ***Figure 1***. However, electrically conductive yarns are pre-

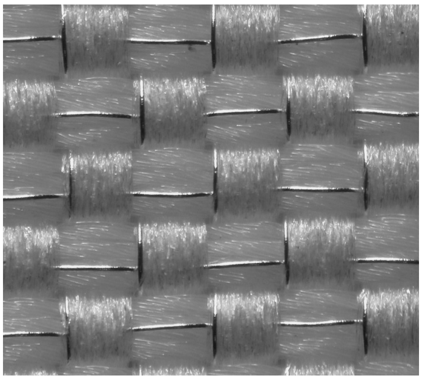

Figure 1. *Conductive path made of copper wires in a woven fabric [5].*

Figure 2. *Textile transmission lines deposited by the printing method [7].*

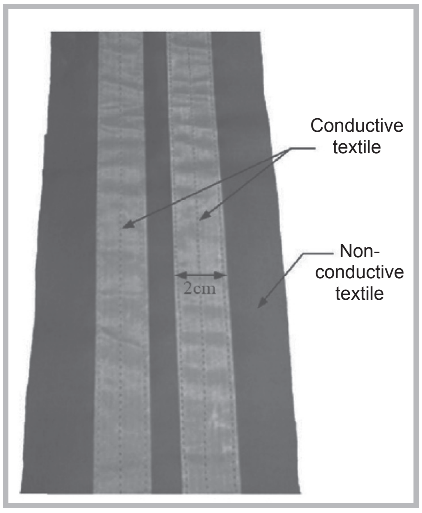

Figure 3. *Textile transmission lines in which the conductive paths are made from a different electroconductive, flat textile [8].*

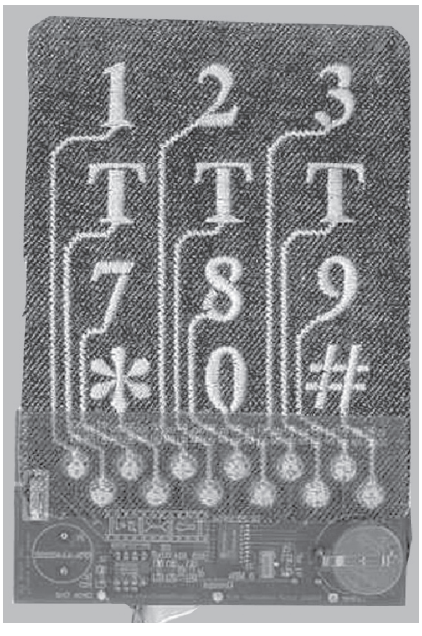

Figure 4. *Embroidered keyboard with connections and electronic circuit [9].*

ferred as they provide better integration with the textile product.

Notwithstanding this, transmission lines made on a textile substrate but with metal wires should also be regarded as a textile line for two reasons: firstly, the textile substrate has a big impact on the electrical parameters of the line, especially in the RF range; secondly, the production of such a line requires knowledge of textile techniques.

In the method of printing, an electroconductive medium in the form of ink containing electroconductive particles, such as gold and silver is deposited on a finished flat textile product using e.g. screen printing. This method is described in more detail in [6]. Example paths made by this method are shown in ***Figure 2***. Research is also being conducted on the use of other types of printing methods such as printing by applying a piezoelectric head. The main problem with this type of printing is the high density of the electroconductive inks, causing trouble with stable printing and frequent clogging of the printing head. A solution to this problem is finding an optimum composition of the electroconductive ink or developing a new construction of the printing head.

Another potential method of the application of a electroconductive medium on flat textile products is the vacuum evaporation method. In this method metal particles are evaporated (sputtered) in a vacuum on the substrate. However, it seems that this method, because of the high costs, will not be applicable in the mass production of transmission lines. An exception may be precise transmission lines operating in microwave frequency ranges, where they can be applied to flexible substrates. In this type of line, the precision of the dimensional geometric shapes of the lines is crucial for their proper operation. Therefore the high cost of such a line is of secondary importance.

The electroconductive paths of textile transmission lines can also be integrated with the textile product by sewing or embroidery. In the first solution conductive paths made from electro-conductive, flat fabric are sewn on the non-conductive textile substrate, as shown in ***Figure 3***. In the second solution, the paths are made of threads, which in this case must conduct electricity. Applying the embroidery technique, with the use of electroconductive threads, conductive paths of the shape and dimensions required can be made (***Figure 4***). In addition, by this method, descriptions of the elements connected can be obtained. An example of a flexible textile keyboard prepared by this technique is presented in ***Figure 4***.

Classification of textile transmission lines and their basic electrical parameters

Textile conductive lines can be divided into power supply lines for electronic circuits, signal lines transmitting signals often with a wavelength much greater than the length of the line (low-frequency signals) and signal lines that transmit signals with a wavelength comparable to the length of the transmission line (high-frequency signals). A special type of such lines are those connecting textronic transmitting devices with textile antennas. In the case of textile lines supplying power to electronic circuits, which are devoted to leading a constant current, the parameters characterising the line are resistance (or resistivity) and the maximum power load of the electrical conductive paths. The efficiency of the transmission of electricity from the power supply to a powered system and the stability of the supply voltage as a function of the load current depend on the resistance of such a line. The efficiency and power line voltage stability on the side of reception decrease with increasing resistance. The good quality of the power supply line depends on its least resistance. The maximum power load is the parameter which, in turn, determines the maximum current limit that can be sent by a power line. Lines with a high rated maximum power load (high maximum current limit) are used, for example, in clothing equipped with heating elements in the form of flat textile products made of electroconductive materials. Technological progress, notable for many years in electronics, brings about a continuous increase in the frequency of electronic components. Increasing the digitisation of electronics makes the signal transmitted increasingly digitised, which is characterised by a broad frequency spectrum. The parameters of transmission lines in the form of printed circuit paths or various types of wires used to transmit such signals have a crucial impact on the quality of transmission. This influence is particularly important in transmitting signals for lines in which the wavelength of the voltage wave is comparable to the length of the transmission line. For this type of line, the number of parameters characterising the properties of transmission is much greater. One of the basic parameters is the characteristic impedance. For a lossless line the impedance can be expressed by the formula:

$$Z = \sqrt{\frac{L}{C}} \tag{1}$$

where:
L – inductance per unit length of the line,
C – capacity per unit length of the line.

In the real transmission line, losses occur in the serial resistance of conductive elements and in the conductance G of the dielectric between these conductive elements, due to the existence of a dielectric resistance value less than infinity. The impedance of such a line takes the following form:

$$Z = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{2}$$

where
R – serial resistance of the conductive line per unit length,
G – dielectric conductance per unit length,
ω – pulsation in rad/s.

The geometric configuration and material properties of the line have an impact on electrical parameters (R, L, G, C) of the transmission line designed. Therefore changes in electrical parameters along the length of the line have an impact on the impedance of the wave line. These changes cause unevenness in the wave impedance along the transmission line, which has a crucial impact on the quality of the electrical signal transmitted by the transmission line. With a large nonuniformity, numerous reflections of the transmitted wave superimposed with the current wave can distort it, hence the information they transmit will be impossible to read.

Other parameters which can be used to characterise the electrical properties of a transmission line are the coefficients s of the matrix. Assuming the use of the four-pole model of the transmission line shown in ***Figure 5*** and applying a sinusoidal voltage of variable frequency at port 1, we can assume that no reflections occur at port 2 ($a_2 = 0$), and hence we can determine the relationship between the incidental wave a_1 and wave voltage b_2 appearing at port 2:

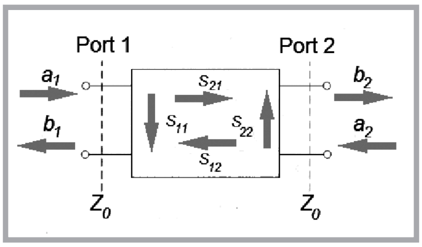

Figure 5. *Four-pole model of the transmission Line with parameters s*

$$s_{21} = \left.\frac{b_2}{a_1}\right|_{a_2 = 0};\ s_{11} = \left.\frac{b_1}{a_1}\right|_{a_2 = 0}. \tag{3}$$

In the same way, after the connection of the wave to port 2, it can be concluded that:

$$s_{12} = \left.\frac{b_1}{a_2}\right|_{a_1 = 0};\ s_{22} = \left.\frac{b_2}{a_2}\right|_{a_1 = 0}. \tag{4}$$

Wave quantities a and b have units of $\sqrt{W}$. In general both incidental waves can have a non-zero character ($a_1 \neq 0$ and $a_2 \neq 0$). This case can be considered as a superposition of the two measurement situations $a_1 = 0$ and $a_2 \neq 0$ with $a_1 \neq 0$ and $a_2 = 0$ [14]. This results in the following equations [14]:

$$\begin{aligned} b_1 &= s_{11}a_1 + s_{12}a_2 \\ b_2 &= s_{21}a_1 + s_{22}a_2 \end{aligned} \tag{5}$$

After groupsetting, we obtain:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \tag{6}$$

In the equations described above, a_i and b_i are defined as:

$$\begin{aligned} a_i &= \frac{u_i + Z_0 i_i}{2\sqrt{Z_0}} \\ b_i &= \frac{u_i - Z_0 i_i}{2\sqrt{Z_0}} \end{aligned} \tag{7}$$

where Z_0 is the characterictic impedance of the line, and u_i and i_i are the voltage and current at port *i*.

On the basis of measurements, we can obtain a complex matrix of parameters s, characterising the electrical parameters of the line at high frequencies. The connection of a voltage sine wave to the input of the test line results in differences between the wave impedance source emitting the signal and the input impedance of the test line (appearance of reflected waves). The presence of a reflected wave causes the appearance of reflection loss. The value of these losses is characterised by coefficients s_{11} and s_{22} of the matrix of parameters s. The wave passing along the test line is also attenuated. These losses are represented by coefficients s_{21} and s_{12} of the matrix of parameters s.

Parameters s are complex values, and therefore they carry information about not only the dependency of the amplitude of the signals but also about their mutual phase shift. Knowing these factors allows a complete analysis of the behaviour of the signal transmitted by the test transmission line.

Another parameter which characterises the quality of the signal line is the attenuation coefficient α, which is one of the components of the propagation constant γ expressed by the formula:

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \tag{8}$$

The higher the value of this factor and the longer the transmission line, the smaller the value of the amplitude of the wave transmitted after passing along the line. For measurement of the electrical parameters described above, we can use one of the well known methods described, for example, in [10] ÷ [14].

Problems connected with the development of textile transmission lines

The design and construction of a new type of textile transmission line encounters numerous problems. A key difficulty is to ensure adequate durability of the line. In normal use each textile transmission line is subject to numerous mechanical stresses, the impact of moisture, perspiration, etc., which can cause line failure and a significant failure rate of the whole textronic system. A separate, very important issue is the maintenance of smart clothing. All elements of the clothing, including transmission lines, should be resistant to washing and other activities associated with periodical maintenance. Currently this problem is often solved by using removable electronic circuits and transmission lines which are removed during the use of clothing. Such elements are usually mounted on the inside of the garment, attached to the outer layer of the clothing with poppers, velcros or zippers. Such a solution would theoretically and radically solve the problem of the maintenance of clothing, but it makes it difficult to use and does not solve the problems connected with the types of exposure occurring during normal use. Moreover, in practice, it often

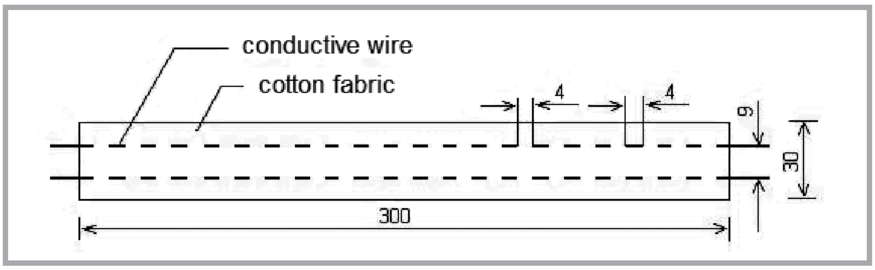

***Figure 6.** Geometrical dimensions of the textile transmission line.*

turns out that during prolonged use of the garment, the detachable part of the clothing, including the electronic systems, is also dirty and needs maintenance, which shows that further work on resistant and durable electronics as well as resistant textile transmission lines is crucial for the further development of textronic clothing. Unfortunately, in the literature available discussing the problem of textronic clothing, the authors largely ignore the impact of ambient parameters on the electrical parameters of the textile transmission lines tested.

However, such an influence exists and is significant for a correct transmission of electrical signals across the line, especially if the signals are transmitted at high frequencies. This phenomenon was shown by initial measurements carried out at the Department of Clothing Technology and Textronics using a FSL 3GHz Rohde-Schwarz Spectrum Analyser equipped with a tracking generator. By means of this analyser the spectral characteristics of the wave passing along and reflected by a transmitting line embedded in fabric were measured in a situation where the background with the line is dry (relative humidity about 40% of the substrate) and moist (relative humidity about 100% of the substrate). The substrate of the test line was a textile cotton woven fabric of plain weave and thickness of 0.52 mm. Two lines made of conductive wire DNE 0.18 mm were woven into the fabric, as shown in ***Figure 6***. The textile signal line was terminated by N-type connectors to connect the test line to the spectrum analyser. The generator output of the spectrum analyser was connected to one end of the transmitting line, while the other end was connected to the input of the same analyser.

A sinusoidal voltage produced by a variable frequency generator, after passing the transmission line, was supplied to the analyser. The characteristics of the wave passing along the dry and wet lines obtained in this way are presented in ***Figure 7***.

In order to record the reflected wave from the line, the transmission line tested was connected to the spectrum analyser using a so-called VSWR bridge. Waveforms of the reflected wave recorded are shown in ***Figure 8***.

The impedance profiles of wet and dry lines were also measured. For these measurements a sampling oscilloscope with Iconnect software was used, the results of which are shown in ***Figure 9***.

The preliminary study shows that with an increase in the humidity of the textile substrate, the attenuation of the signal transmitted also increases. From the analysis of waveforms shown in ***Figure 7***, we can conclude that the attenuation of the passing wave for specific frequencies is, by an average of several dB, lower for the dry transmission line. The scattering attenuations versus the frequency for the dry and wet lines are less important than the average of the attenuation values for these lines. The study also showed that an increase in moisture content causes an increase in losses due to the increase in the reflected wave in the line. In conclusion, a dry line has better transmission properties than a wet line. As shown in ***Figure 9***, an increase in the moisture content of the line also causes changes in the impedance profile of the line, which affects the matching of line and distortions of the signal transmitted.

Another key problem in the construction of a line is that of the impact of mechanical stress on the stability of the electrical parameters of the line. In the case of lines fitted to transmit a high frequency or wide frequency spectrum signals, the solution to this problem is a serious chal-

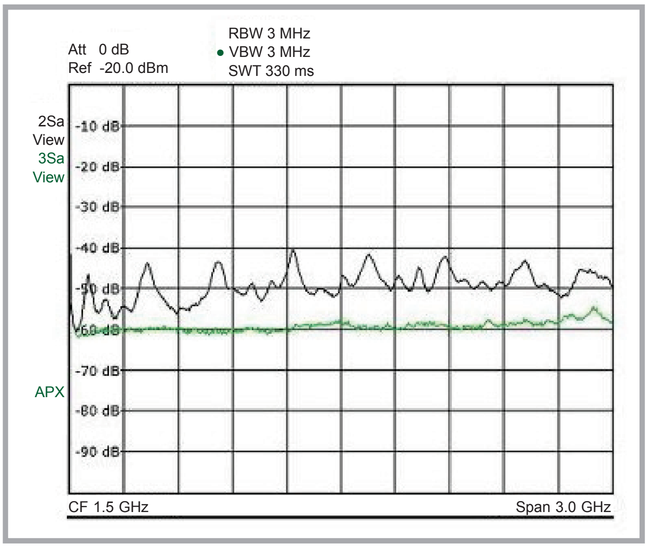

***Figure 7.** Spectral characteristics of a wave passing along the dry (upper waveform) and wet (bottom) transmission line.*

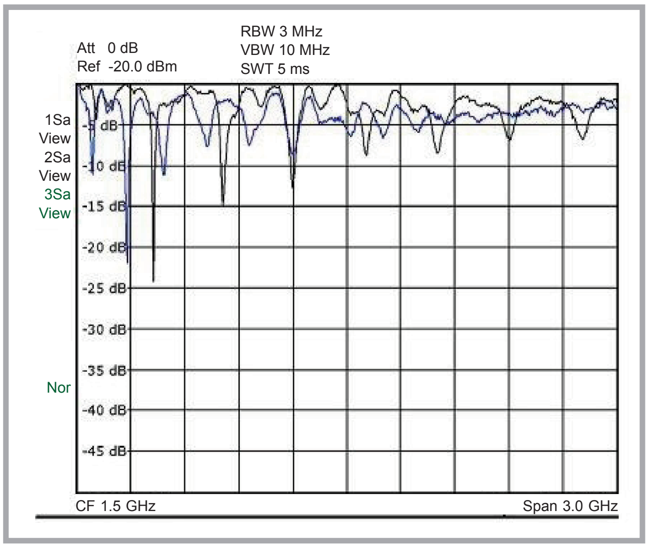

***Figure 8.** Spectral characteristics of the reflected wave from the dry (bottom) and wet (upper waveform) textile transmission line.*

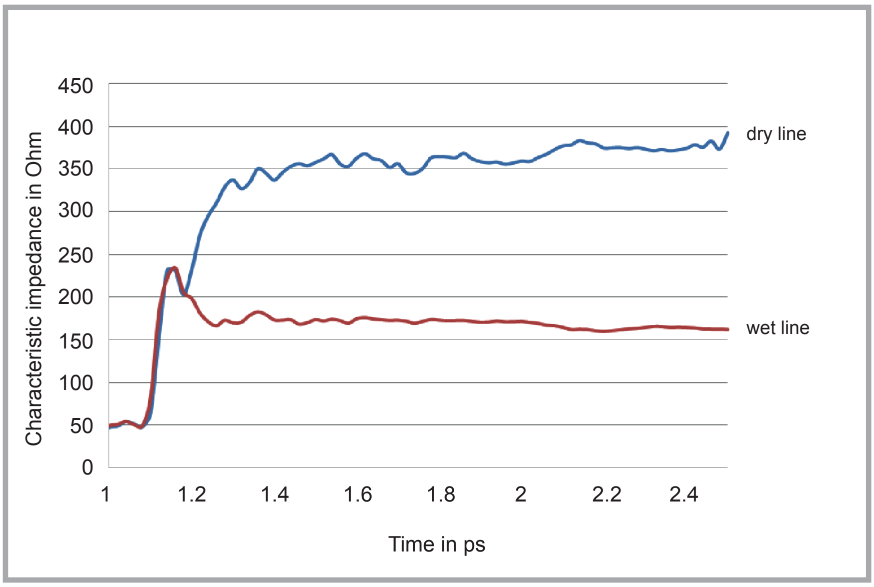

Figure 9. *Impedance profiles of the wet and dry textile transmision line.*

lenge to the constructor, which nevertheless must be solved.

Conclusions

There are many methods of implementing a textile transmission line. The choice of the right method depends on the particular application, the frequency range, the cost of production, etc.

As a result of the preliminary study, we found that the humidity of the substrate of the textile transmission line has a significant impact on the ability to transmit signals with a wide spectrum of frequencies. Further work on the development of textile signal lines capable of transmitting the high frequency signals often found in current electronic circuits and also resistant to ambient parameters, mechanical stresses and periodic maintenance service will have a crucial impact on the development of the textronic garment.

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